COASTAL EVOLUTION MODELING AT MULTIPLE SCALES IN REGIONAL SEDIMENT MANAGEMENT APPLICATIONS

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Abstract: A numerical model called GenCade is introduced that simulates shoreline change relative to regional morphologic constraints upon which these processes take place. The evolution of multiple interacting coastal projects and morphologic features and pathways, such as those associated with inlets and adjacent beaches can also be simulated. GenCade calculates longshore sediment transport rates induced by waves and tidal currents, shoreline change, tidal inlet shoal and bar volume evolution, natural bypassing, and the fate of coastal restoration and stabilization projects. It is intended for project- and regional-scale applications, engineering decision support, and long-term morphology response to physical and anthropogenic forcing. Capabilities of the model are illustrated by an application to the south shore of Long Island, NY. The Long Island application has multiple coastal structures and features that are maintained to varying degrees of frequency. Cumulative response of the beaches from a variety of coastal projects leads to complexity in regional coastal management. GenCade is presented as a tool to unify management of local projects at regional scales.

Introduction

Shoreline change (one-line) models such as GENESIS (Hanson and Kraus 1989) and profile evolution models such as SBEACH (Larson and Kraus) have proven their predictive capabilities in numerous engineering projects conducted worldwide. However, a major limitation in their approach is lack of coupling between long-shore (LS) and cross-shore (CS) processes. Coupling is required from a physical point of view, because of: gradual LS change by alongshore currents; and gradual CS change by wind-blown sand and sea level change; and more intense CS change by episodic storms necessarily form a coupled system. Also, from a modeling perspective, separate treatment of the two processes offers the modeler a complicated, inefficient, and unresponsive way of accounting for the two processes.

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The response of the coast to climate change (water level, waves, wind; frequency and intensity of storms) highlights the need for a modeling system that is capable of operating on several time and space scales. Omission of gradual changes, such as relative rise (or change) in sea level, makes long-term simple extrapolation unrealistic. Because projects typically have lives exceeding their initial 50 years, there is a need for models capable of reliably, robustly, and rapidly calculating coastal evolution over decades to centuries for evaluation of many planning and engineering alternatives. An expected increase in storm frequency and intensity will most likely mean that these short-term processes will increasingly contribute to long-term evolution of the coast. From experience with previous coastal projects, we have learned the importance of regional processes (e.g., shadowing from large land masses, sand storage and transfer at inlets) on a local beach. Realistic representation of these processes requires modeling on several spatial and temporal scales. Long simulation times over large areas can only be performed with realistic computational effort. The interaction between waves, structures, and morphological processes needs to be represented but at a resolution that allows for calculation at the regional scale.

This paper presents a new coastal evolution model called GenCade. The goal of GenCade is to simulate LS and CS sediment transport processes, including morphologic responses to engineering actions, and interactive shoreline, dune, and inlet evolution, on the scale of hundreds of years, a regional and long-term perspective. The regional model provides appropriate boundary conditions for conducting engineering-design level studies on sub-reaches of the model grid. Sediment budgets along a chain of beaches and inlets thus become compatible and integrated. To achieve design calculations within a regional context, irregular grid spacing has been implemented in GenCade.

The objective of this paper is to demonstrate the capability of GenCade to efficiently and accurately calculate significant shoreline and inlet shoal evolution processes at combined local and regional scales over many decades. GenCade capabilities are demonstrated through an RSM application presented for Long Island, NY, USA, which extends over scales of approximately 100 km with regionally curved morphology, numerous inlets, and multiple coastal engineering activities including inlet dredging, beach fills, ebb-tidal delta mining, jetties, seawalls, and groins.

GenCade

GenCade is a newly developed model for calculating coastal sediment transport, morphology change, and sand bypassing at inlets and engineered structures. Based on the synthesis of the GENESIS model (Hanson and Kraus 1989) and the Cascade model (Larson *et al.* 2002) it combines project-scale, engineering

design-level calculations with regional-scale, planning-level calculations to analyze and accurately resolve both local modifications and regional cumulative effects of coastal projects and inlets. This has been made possible by the introduction of variable grid resolution and by defining a regional trend that maintains the regional overall coastal shape.

GenCade has been integrated into the Surface-Water Modeling System (SMS) Graphical User Interface for model grid and forcing development, simulation execution, data pre/post-processing, and seamless integration with other model and data applications working in real-world coordinate systems.

Tidal Inlets

Morphology change at inlets and their interaction with adjacent beaches is of great importance for many coastal areas. GenCade employs the Inlet Reservoir Model as first presented in Kraus (2000) and further developed by Larson *et al.* (2002; 2006). Each inlet is represented by six morphological elements (shoals and bars) plus the inlet channel (Fig. 1). Each morphological element is, in turn, represented by an actual volume V_x and an equilibrium volume V_{xq}, where x stands for a (attachment bars), b (bypass bars), e (ebb shoal), or f (flood shoal). The flux of sediment out of each morphological element is given by:

$$Q_{ox} = Q_{ix} \frac{V_x}{V_{xq}} \tag{1}$$

where Q_{ox} represents the flux out of the element x and Q_{ix} the flux into the element. In Fig. 1 the transport goes from left to right. A transport rate Q_{lst} is moving alongshore towards the inlet, which may or may not be stabilized by a jetty. If there is a jetty, a portion of this sediment Q_j will be trapped by the jetty (thus, when no jetty, Q_j=0) whereas the remaining part Q_{in} will enter into the inlet system. A part of this rate $Q_{ie} = \delta Q_{in}$, depending on how full the ebb and flood shoals are, continues to the ebb shoal while the other portion Q_{ic} will go into the inlet channel. This will, in turn, feed the ebb and flood shoals in proportion to their relative volumes. Unless the system is completely full, a portion of the incoming rate Q_{out} will leave the inlet system and be transported further along the beach. If transport rates are going in the opposite direction, the bars on the left hand side will be activated whereas the ones on the right hand side will be passive. Initial and equilibrium volumes are specified as input values to the model as are the respective locations of the attachment bars.

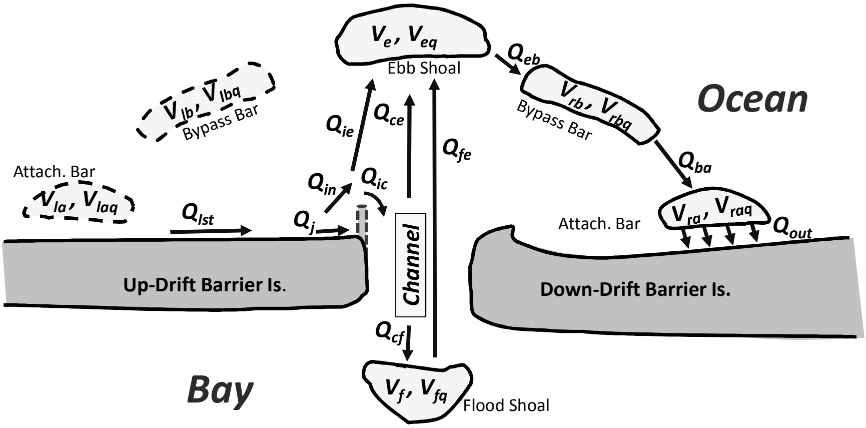

Figure 1. Schematic of the interaction between the morphological elements in an inlet. Bar volumes on the left-hand side of the inlet are denoted by subscript *l* and on the right-hand side by subscript *r*.

Dune Erosion

As waves run up on the beach and reach the foot of the dune, the dune will be subject to erosion. If it is assumed that no overwash occurs and that the dune is not completely eroded (*i.e.* no breaching), the erosion rate due to wave impact on the dune may be estimated as (Larson *et al.*, 2004; Hanson *et al.*, 2010):

$$q_o = 4C_s \frac{(R' + \Delta h - z_D)^2}{T}, \qquad R > z_D - \Delta h \tag{2}$$

where R' is the adjusted run-up height (including setup), Δh is the surge level (including tide elevation relative to mean sea level (MSL)); z_D is the dune toe elevation (with respect to MSL); T is the swash period (taken to be the same as the wave period); and C_s is an empirical coefficient. The adjusted run-up height is calculated from:

$$R' = R\exp\left(-2k_f s_B\right) + z_D\left[1 - \exp\left(-2k_f s_B\right)\right] \tag{3}$$

where R is estimated from $R = a\sqrt{H_o L_o}$, in which H_o is the deepwater root-mean-square wave height, L_o is the deepwater wavelength, and a is a coefficient (about 0.15, which corresponds to a representative foreshore slope); k_f is a friction coefficient, $s_B = y_B - y_D$ (see Fig. 2). Eq. (3) accounts for the reduction

in impact as the berm height gets wider. In the numerical implementation, q_o varies at each time step and is computed from the input time series of waves.

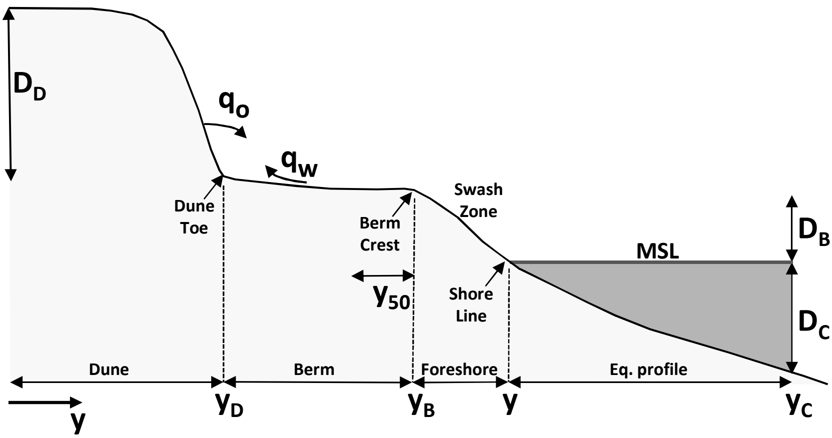

Figure 2. Definition sketch of dune, berm, foreshore, and associated notation.

Dune Recovery

The dune is allowed to recover through eolian transport by sand blowing from the berm. It is assumed that sand transport to the dune is related to the width of the berm up to some distance over which equilibrium conditions have developed, implying that beyond equilibrium a wider beach does not generate more transport by wind, (Davidson-Arnott and Law, 1990; Davidson-Arnott *et al.,* 2005). A simple equation that exhibits these properties, with a slow but gradual increase of the transport rate by wind with beach width for narrow beaches, a stronger increase for wider beaches, and an upper limit that is approached gradually for wide beaches, while at the same time providing a continuous description of the transport with changes in berm width, is:

$$q_w = q_{wo}\left(1-0.5\left(1-\tanh\left[\frac{\pi}{q_{grad}}\left(y_B - y_D - y_{50}\right)\right]\right)\right) \tag{4}$$

where q_{wo} is the maximum transport by wind for an infinitely wide beach, dependent on wind speed, water and sand properties, y_B and y_D are the distances to the seaward end of the berm and the dune toe, respectively (see Fig. 2), with the y-axis pointing offshore, y_{50} is the distance from the seaward end of the berm

to where the wind-blown transport has reached 50% of its maximum, and q_{grad} is the transport gradient at y_{50}. Bagnold (1954) suggested the transport rate relationship $q_{wo} = K_w u_*^3 / g$, where u_* is the wind shear velocity, g is the acceleration due to gravity, and K_w is an empirical coefficient that quantifies the influence of sand properties on the transport rate. Eq. (4) describes a dune that advances towards the berm crest, although the rate of advance will decrease with time as the berm width decreases. In the model calculations, q_{wo} is held constant in time, corresponding to an average wind speed.

Coupling of Processes

Under the assumption that dune and beach profile change occur while maintaining their respective shape, continuity requires that:

$$\Delta y_B = -\Delta y_D \frac{D_D}{D_B + D_C} \tag{5}$$

where Δy_B is the berm crest translation corresponding to a dune foot translation Δy_D, D_D is the dune height, D_B is the berm height, and D_C is the depth of closure. This equation provides a simple estimate of the needed profile recession due to cross-shore processes, from the foot of the dune to the depth of closure, to produce a certain dune advance, and vice versa. Next, the cross-shore exchange between the berm and dune is combined with the alongshore sand transport rate caused by obliquely breaking waves through the continuity equation of shoreline change:

$$\frac{\partial y}{\partial t} = -\frac{1}{D_B + D_C}\left(\frac{\partial Q}{\partial x}\right) + \frac{\partial y_B}{\partial t} = -\frac{1}{D_B + D_C}\left(\frac{\partial Q}{\partial x} - q_o + q_w - q_{bp}\right) \tag{6}$$

where y is the shoreline location, t is time, Q is the longshore transport rate, and q_{bp} is a portion of Q_{out} distributed along the beach section inside the down-drift attachment bar. Thus, the down-drift release of sediment from the tidal inlet system and the berm translation due to cross-shore interaction between the dune and berm are linearly added to the contribution by the gradient in longshore transport rate, $\partial Q / \partial x$, to obtain the total shoreline temporal evolution.

GenCade Application: Long Island, NY

Background and Method

A GenCade model application is presented for the south shore of Long Island, NY as a validation of relevant processes over multi-decadal time scales. The south shore of Long Island (Fig. 3) was selected as an appropriate test site for examining the capabilities of GenCade because of the availability of a long-term regional coastal database and because the site includes multiple inlets and barrier islands with coastal structures and ongoing coastal projects that are maintained at irregular intervals. The data and morphological composition of the site provide a challenging application to test the unified coastal predictive capabilities of GenCade. The model domain extends from Montauk Point in the east to East Rockaway Inlet in the west and includes four inlets: Shinnecock Inlet, Moriches Inlet, Fire Island Inlet, and Jones Inlet.

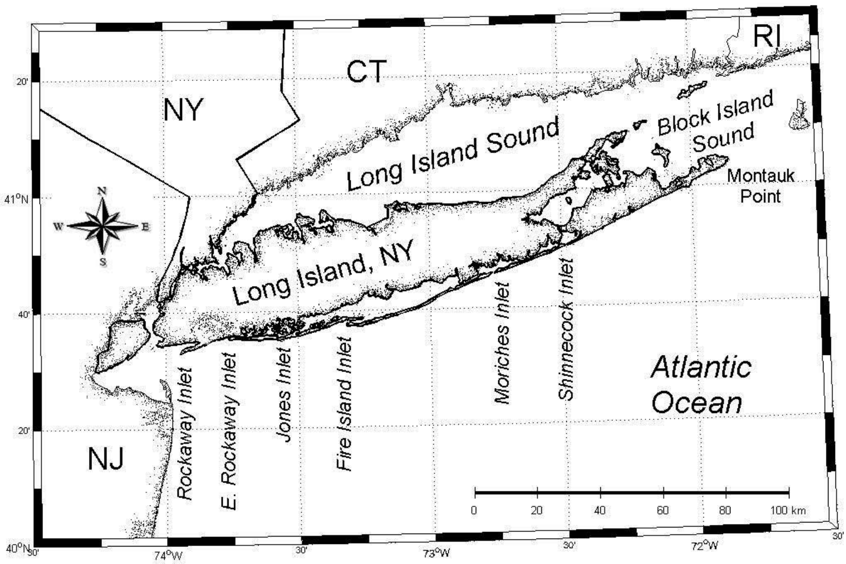

Figure 3. Location Map listing all the maintained inlets on the south shore of Long Island.

The wave climate along the south shore of Long Island is characterized by moderate Atlantic waves typically from the southeast quadrant with a relatively strong seasonal component of fairly mild waves during summer, severe waves associated with extratropical storms frequent during winter and spring, and severe waves associated with tropical storms during fall. Mean wave height over

a 25-year period at NOAA NDBC buoy 44025 is 1.2 m and mean wave period is 8 s. One recent study has estimated 50-year and 100-year return period waves at 16.0 m and 17.1 m, respectively (NYSERDA 2010). Nearshore waves are substantially reduced in energy as waves shoal across the shelf and Wave Information Study (WIS) station 50-year storm waves are estimated at 8.7 m. The wave climate at this location shows that the majority of waves are from the southeast and the more severe waves associated with extratropical storms are from the east-southeast. This results in a net westerly longshore transport direction along the studied coast.

The general trend in grain size characteristics decreases in diameter from Montauk Point where cobbles are common due to the proximity to the glacial outwash at the Ronkonkoma moraine. Coarse sand beaches are typical immediately west of Montauk Point and median grain size changes from approximately 0.5mm immediately west of Montauk to 0.2 mm in the vicinity of East Rockaway Inlet (Taney 1961; Morang 1999; USACE 2006). A total beach fill volume of 1,150,000 m^3 has been placed along the beach west of Shinnecock Inlet from 1983-1995 (Morang 1999) and these are incorporated into the model simulations.

The simulations generally follow the procedure conducted by Larson *et al.* (2002) to determine regional consistency between GenCade and Cascade. Additional simulations are conducted with the same grid to examine the sensitivity to ebb shoal excavation of the beach fill material (e.g., dredged from local inlets within this littoral cell) compared to fill brought in to the littoral system (e.g., trucked in). The modeling represents sediment bypassing and tidal shoal evolution at Moriches Inlet and Shinnecock Inlet, as well as 15 groins along Westhampton, which have interrupted the sediment supply to Moriches Inlet and Fire Island and require fine spatial resolution to capture relevant morphology change between the narrowly spaced groins. The present study also incorporates barrier islands further west of Fire Island Inlet including the chronically erosive segment also containing groins near Point Lookout west of Jones Inlet. This section of the grid was developed following the existing conditions with all groins along Point Lookout Beach, Hempstead Beach, and Long Beach outlined in Beck and Kraus (2010).

A 12-year simulation (1983-1995) was executed, forced by WIS stations 75, 78, and 81. There were 934 grid cells, with cell resolution variable alongshore from approximately 50 m to 200 m, where grid cells with higher resolution applied to areas with groins and jetties. The computational time step was 1 hour, a constant grain size of 0.3 mm with an average berm height of 1 m was employed, constant depth of closure was set to 8 m, and a “pinned” (*i.e.*, no shoreline change) boundary condition was employed at both lateral ends. Calibration of

the model consisted of first adjusting K1 and K2 values to result in transport rates that were consistent with sediment budget derived transport rates at various locations in the domain. Next, calculated shoreline after the simulation was compared to measured shoreline for agreement. After the initial calibration period, K1 was set to 0.30 and K2 to 0.15.

Results

The simulations at Long Island (Fig. 4) demonstrate that GenCade is in close agreement with results compiled in Rosati *et al*. (1999) based on a sediment budgets for eastern Long Island. The results are not identical to the Cascade calculations presented by Larson *et al*. (2002) because the input parameters and numerical method for GenCade are different and at higher resolution than those presented for Cascade. For example, GenCade supports variable grid resolution and representation of greater engineering structure design details, which improves capability to more accurately represent the inlets and groins in the domain. Net transport rates were also cited as approximately 200,000 cy/yr along the barrier west of Jones Inlet (USACE 2006). This is consistent with the results shown in Fig. 4.

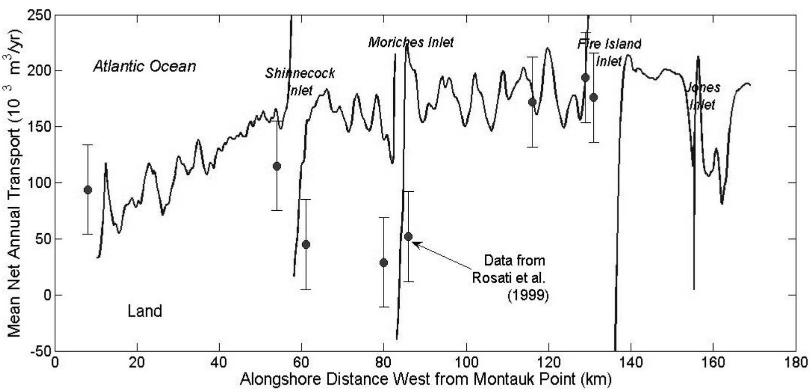

Figure 4. Calculated average transport rate for south shore of Long Island, NY.

Figure 5 presents a comparison of the GenCade calculated shoreline after the 12-year simulation compared to a measured 1995 shoreline and the initial 1983 shoreline. Regionally, the calculated shoreline is in close agreement with the measurements. It is clear that the regional morphological trend is maintained over the entire length of the domain. Over the majority of local areas, the shoreline calculations agree with the measurements as well; however, there are

some regions near the inlets with greater erosion than is shown in the measured shoreline. This could be linked to sensitivity of the position of the inlet bypassing bar and attachment point. The greatest error is calculated at Fire Island Inlet. Fire Island Inlet is a barrier over lap inlet with a prograding spit that continues migrating west. GenCade does not currently handle spit development or growth, which is likely contributing the calculated error at Fire Island Inlet.

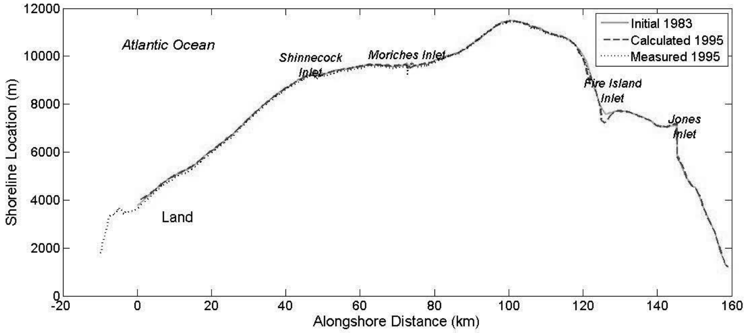

Figure 5. Calculated and measured shoreline position, for south shore of Long Island, NY.

Figure 6 shows the calculated volume evolution of the ebb shoal complex at Shinnecock Inlet and Moriches Inlet relative to ebb tidal delta volumes calculated from field measurements by Morang (1999). These results show relatively close agreement with the measured data, but the rapid increase in volume observed in the late 1990s is not represented in the model calculations. As the calculated curves approach the equilibrium volume rapid expansion of the ebb shoal complex becomes less likely without a major influx of sediment into the inlet. Figure 6 also depicts the calculated volumes at the ebb shoal complex with and without dredge excavation of the ebb shoal. The differences between the two curves show the shoal recovery potential when comparing shoal mining at local inlets versus importing beach fill from external sources. These calculations have significant value to coastal management as the modifications to the shoals also impact transport rates and shoreline erosion at beaches in the vicinity of the inlets.

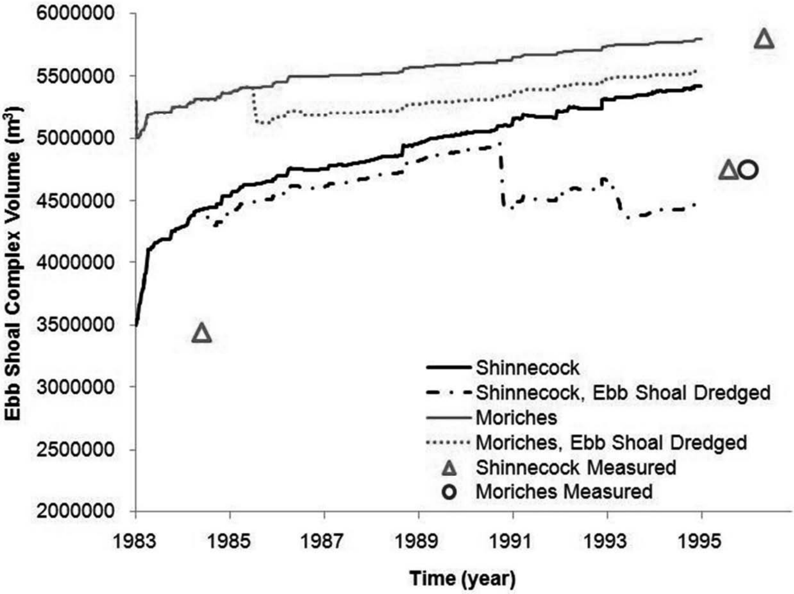

Figure 6. Calculated (a) ebb tidal delta volume evolution with and without ebb shoal dredging.

Concluding Discussion

A numerical model, called GenCade, was presented. It combines project-scale, engineering design-level calculations with regional-scale, planning-level calculations to analyze and accurately resolve both local modifications and regional cumulative effects of coastal projects and inlets. Application of the model to the south shore of Long Island, NY, demonstrated the capability to calculate cumulative coastal structure impacts over large regional domain and over long time periods while preserving regional geomorphic trends. The impact of dredging on shoal recovery was also demonstrated at two inlets in Eastern Long Island. Limitations of GenCade include: the limited cross-shore process calculation, single grain size across the full model domain, no means of calculating migration of inlets or newly opening inlets, and there is currently no method implemented to handle spit evolution such as what occurs at an overlay barrier inlet such as Fire Island Inlet. Many of these limitations have become opportunities for present and ongoing development of model routines and methods to address the limitations either directly or by parameterizing the processes for efficiency.

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